5.1 **Boundary Layer**

5.1.1 Introduction

It is a well established fact by experiment that when a fluid flows over a solid surface there is no slip at the surface. The fluid in immediate contact with a surface moves with it, and the relative velocity increases from zero at the surface to the velocity in the free stream through a layer of fluid which is called the boundary layer.

Consider steady flow over a flat smooth plate as shown in Fig. 1, where the freestream velocity is U . It is found that the thickness of the boundary layer is laminar at the start, but if the plate is sufficiently long, a transition to turbulence is observed. This transition produced by small disturbances which, beyond a certain distance, grow rapidly and merge to produce the apparently random fluctuations of velocity which are characteristics of turbulent motion.

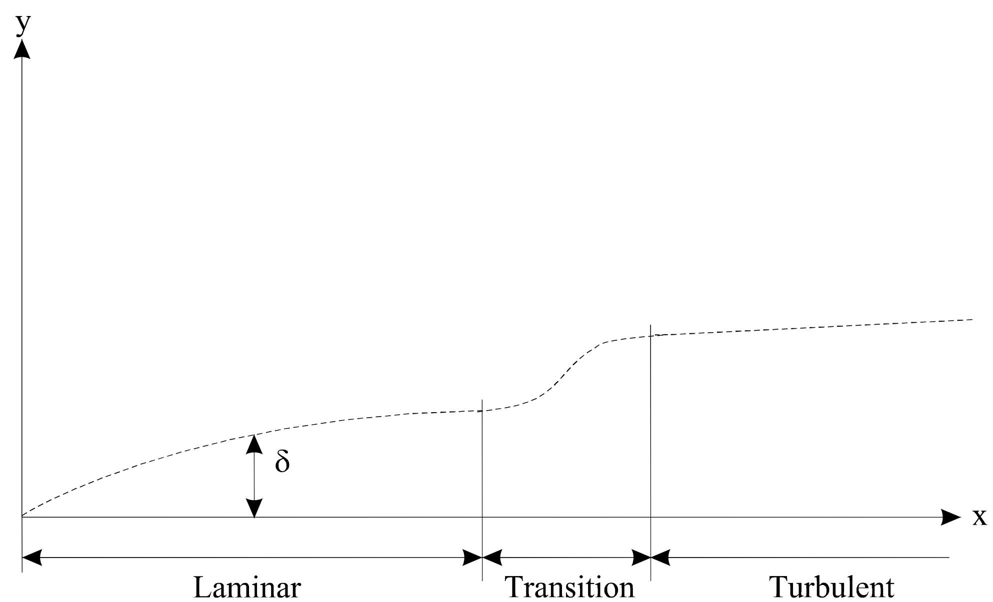

Figure 1: General Characteristics of Boundary Layer over a Flat Plate.

The parameter that characterizes the position of the transition is the Reynolds number Re based on distance x from the leading edge.

$$Re_x = \frac{Ux}{\nu} \tag{1}$$

where ν is the fluid kinematic viscosity.

The nature of the transition process is prone to factors such as turbulence in the free stream and surface roughness of the boundary, such that it is not possible to give a single value of Re_x at which transition will occur. It is usually found in the Reynolds number range of $1x10^5$ to $5x10^5$.

5.1.2 Boundary Layer Thickness

The boundary layer thickness δ, shown in Fig. 1 as the thickness where the velocity reaches the free stream value, is not an entirely satisfactory concept. This edge cannot be observed in an actual flow since the velocity increases towards U in an asymptotic manner. Arbitrarily the edge has been defined as 99% of the free stream value. The boundary layer thickness is a very thin layer. Therefore we can approximate the velocity profile for both laminar and turbulent flow with reasonable accuracy.

The laminar boundary layer over a flat plate with zero pressure gradient has four boundary conditions that must be met. They are

$$\begin{aligned}
u &= 0 && \text{at} \quad y = 0 \\
u &= U && \text{at} \quad y = \delta \\
\frac{\partial u}{\partial y} &= 0 && \text{at} \quad y = \delta \\
\frac{\partial^2 u}{\partial y^2} &= 0 && \text{at} \quad y = 0
\end{aligned} \tag{2}$$

A cubic polynomial can meet these four conditions. Below is the form of the polynomial.

$$\frac{u}{U} = a + b\left(\frac{y}{\delta}\right) + c\left(\frac{y}{\delta}\right)^2 + d\left(\frac{y}{\delta}\right)^3 \tag{3}$$

Applying the boundary conditions to this polynomial results in the following velocity profile.

$$\frac{u}{U} = \frac{3}{2}\left(\frac{y}{\delta}\right) - \frac{1}{2}\left(\frac{y}{\delta}\right)^3 \qquad (4)$$

The continuity and momentum equation for the boundary layer in integral form can be presented in the form of von Karman's integral equation.

$$\tau_o = \frac{d}{dx}\int_0^{\delta} \rho u(U-u)dy \qquad (4)$$

where τ_o is the shear stress at the wall. Development of this integral is provided in many fluid mechanics textbooks. Substituting the velocity profile into the integral results in the equation for the boundary layer thickness.

$$\delta = 4.65\frac{x}{\sqrt{\mathrm{Re}_x}} \qquad (5)$$

Frequently the velocity distribution for turbulent flow is expressed in the form

$$\frac{u}{U} = \left(\frac{y}{\delta}\right)^{\frac{1}{n}} \qquad (6)$$

where n is an index that varies from about 5 to 8 as the value of Re_x increases in the range of 10^5 to 10^9. This expression is referred to as the power law velocity profile. For Re less than 10^7, n is equal to 7. Using this profile in von Karman's integral along with an empirical relation Blausius formula results in the following boundary layer equation.

$$\delta = 0.38\frac{x}{\mathrm{Re}_x^{1/5}} \qquad (7)$$

It is assumed that the laminar portion of the boundary is quite short that it is neglected.

5.1.3 Description of Apparatus

Figure 4 shows the arrangement of the test section attached to the outlet of the contraction of the airflow bench. A flat plate is placed at mid height in the section, with a sharpened edge facing the oncoming flow. One side of the plate is smooth and the other is rough so that by turning the plate over, results may be obtained on both types of surface.

A fine pitot tube may be traversed through the boundary layer at a section near the downstream edge of the plate. This tube is a delicate instrument that must be handled with extreme care if damage is to be avoided. The end of the tube is flattened so that it presents a narrow slit opening to the flow. The traversing mechanism is spring loaded to prevent backlash and a micrometer reading is used to indicate the displacement of the pitot tube.

Liners may be placed on the walls of the working section so that either a generally accelerating or generally decelerating free stream may be produced along the length of the plate, depending on which way round they are fitted. With the liners removed, uniform free stream flow conditions are obtained over the plate length.

5.1.4 Experiment Safety

- Be careful plugging the blower into the wall socket.
- Do not place any loose articles on the work bench table top.
- Do not place body or any other part of the body inside apparatus during operation.

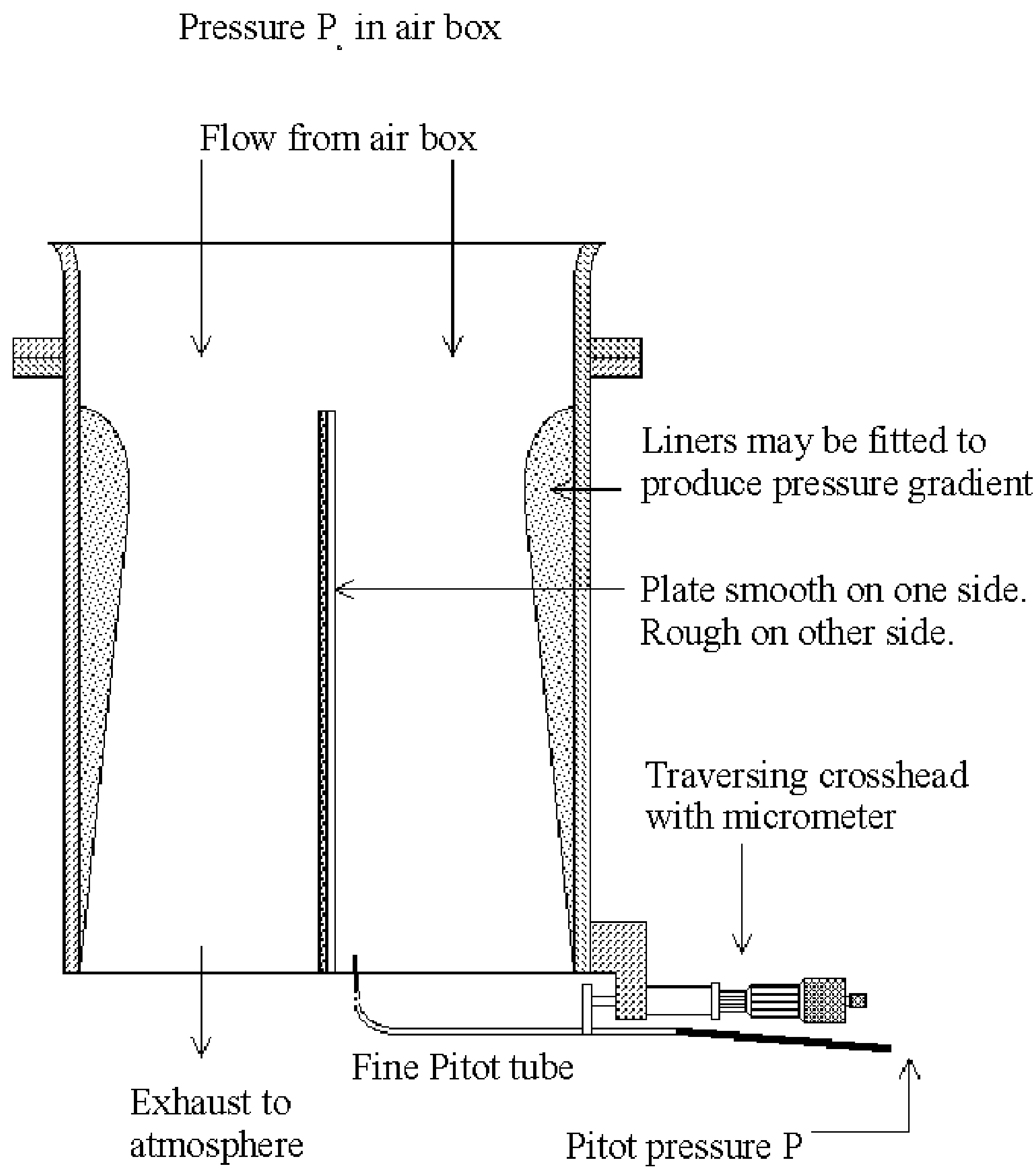

Figure 4: Arrangement of Test Section

Boundary Layer Worksheet

The steps to run the experiment are given below. The data should be written in the tables provided, as well as the calculated values. Note all data should include the uncertainty.

1. List objectives of this experiment.

2. Place the smooth side of the plate such that it is facing the pitot tube. Remove the liners.
3. Make sure the blower setting valve is completely closed.
4. Turn on blower.
5. Slowly open valve to medium setting.
6. Set the pitot tube at a distance from the plate surface where it is just outside the boundary layer.
7. Determine the freestream air velocity.

Freestream velocity __________________ m/s

8. Record the micrometer setting.

__________________ mm

9. Record atmospheric temperature and pressure from air bench instruments.

________________ C __________________ kN/m^2

10. Predict boundary layer thickness

Calculations:

_________________ mm

11. Record air box pressure, P_o .

_________________ mbarr

12. Record readings of total pressure P measured by the pitot tube over a range of settings of the micrometer as the tube is traversed towards the plate. Table 2 is provided for recording data. At first the readings should be substantially constant, indicating that the traverse has been started in the free stream; if this is not the case, go back and start with an initial setting further from the plate. As the pitot tube reading begins to fall, the step length of the traverse should be reduced so that at least ten readings are obtained over the range of reducing readings. The reading does not fall to zero as the tube touches the wall because of its finite thickness. The traverse should be stopped before contact is made. Readings obtained in turbulent boundary layers are subject to unsteadiness which leads to difficulty in obtaining average readings on the manometer. Damping may be provided by squeezing the connecting plastic tube, but care should be taken that the restriction is not too severe, which can lead to false readings.
13. Turn off blower.
14. Close valve.
15. Complete calculations in data table.
16. Plot y versus u/U from the data. Also include theoretical plot.

Table:

Micrometer Reading (mm)	y (mm)	P (mbarr)	u/U

Discussion of Results and Conclusions